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Review of Solid State Photon Counters for Laser Tracking of Orbital Space Debris

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Abstract. *We are reporting on a design, construction and performance of various solid state photon counting detector packages suitable for laser tracking of orbiting space debris. Our group has designed and constructed several solid state photon counters for application in space related projects in the last years. In all these earlier applications the timing resolution, stability and operation at 532 nm wavelength were the key requirements. In contrast to it laser ranging of orbiting space debris requires ultimately high photon detection probability, while the timing parameters are of lower importance. A detector package providing photon detection probability exceeding 70% at 532 nm wavelength has been developed for space debris laser ranging. It is used for this purpose on several SLR stations worldwide. The foreseen new systems for orbiting space debris laser tracking are expected to operate on near infrared wavelengths 1064nm or 1540 nm. We are presenting a review of photon counting detectors candidates for space debris laser tracking.*

Introduction

Laser ranging to non-cooperative orbiting space targets – space debris - represents a new challenge for the satellite laser ranging (SLR) community. The absence of a laser retro-reflector is resulting in an extremely weak echo optical signals in comparison to a standard SLR case. Depending on a space debris cross section its echo optical signal strength is typically several orders of magnitude lower in comparison to a retro-reflector equipped target at a same distance. That is why the overall experiment energy budget is a key issue of orbiting space debris laser ranging. There exists an obvious need for high power laser transmitters and top photon detection probability receivers. Most of the SLR systems are operating on a wavelength of the second harmonic frequency of Nd:YAG laser, corresponding to 532 nm. This wavelength may be detected by silicon based photon counting receivers. Recently the attractive option for orbiting space debris laser ranging seems to be high power pulsed laser operating in a near infrared region. Of special interest are the wavelength of 1064 nm (fundamental wavelength of Nd:YAG) and namely the 1540 nm region. In this wavelength region the permitted maximum eye exposure is several orders higher in comparison to a visible region, high power pulse lasers are available. However, the design, construction and application of photon counters for this wavelength is a technological challenge.

Photon counting detectors on silicon

Our group has designed and constructed several solid state photon counters for application in space related projects in the last years (Prochazka et al., 2011; Meng et al., 2013). We have been developing and providing photon counting detectors for ground based satellite laser ranging and

laser time transfer systems. These detectors have been used for the initial experiments of space debris laser ranging (Kirchner et al., 2012). Photon detection probability of these detectors is modest: about 40 % @ 532 nm. That is why we have developed and tested a new photon counting detector providing higher photon detection efficiency while maintaining acceptable timing resolution and detection delay stability.

The commercially available single-photon avalanche diode SAP500 (Laser Components. Inc.) has been used (Stipcevic et al., 2010). Its active area diameter is relatively large 0.5 millimeter, its breakdown voltage is typically 100 Volts. This detection chip has been extensively tested by M. Stipcevic and co-workers mainly for applications in quantum communication and quantum key distribution experiments. They did measure, among others, the photon detection efficiency of 73 % at the wavelength of 540 nm. We have developed a new electronic control circuit and we have constructed an entire detector package for laser ranging applications. The entire detector consisting of a detection chip with cooling, electronic control circuit and collecting optics is assembled in a standard SPAD housing with dimension of 50×50×130 millimeters, the compact power supply and cooling control unit has been constructed as well, see Figure 1.



Figure 1

The SAP500 detection chip in housing with a single stage thermoelectric cooling is used. The built in temperature sensor is used to control the thermoelectric cooling and hence to stabilize the detection chip temperature at -8 ± 0.1 °C. The incoming light in form of a collimated beam is collected by a fast optics $f/D = 0.8$ consisting of an air spaced doublet with antireflection coating. The clean optics aperture is 15 mm in diameter.

The detector timing tests were completed in a Time Correlated Single Photon Counting (TCSPC) experiment. The optical pulse source was a Hamamatsu diode laser PLP-02 delivering 42 ps long pulses at the wavelength of 778 nm. The dependence of the detector key parameters on a bias above its breakdown voltage is summarized in Figure 2.

From this Figure one can conclude that for the best timing resolution and detection efficiency the bias above break of 50 Volts has to be selected. However, the dark count rate at this bias is rather high. That is why the bias above breakdown in a range of 15 to 20 Volts is frequently selected as a trade-off between dark count rate, detection efficiency and timing resolution. In all the next experiments the SPAD bias was set to 16 Volts above its breakdown voltage. The timing resolution of 70 ps r.m.s. has been measured in a setup in which all the active area of the detection chip has been uniformly illuminated. In an optical setup where the photons were focused on a small spot near the center of an active area the timing resolution as low as 42 ps r.m.s. has been achieved

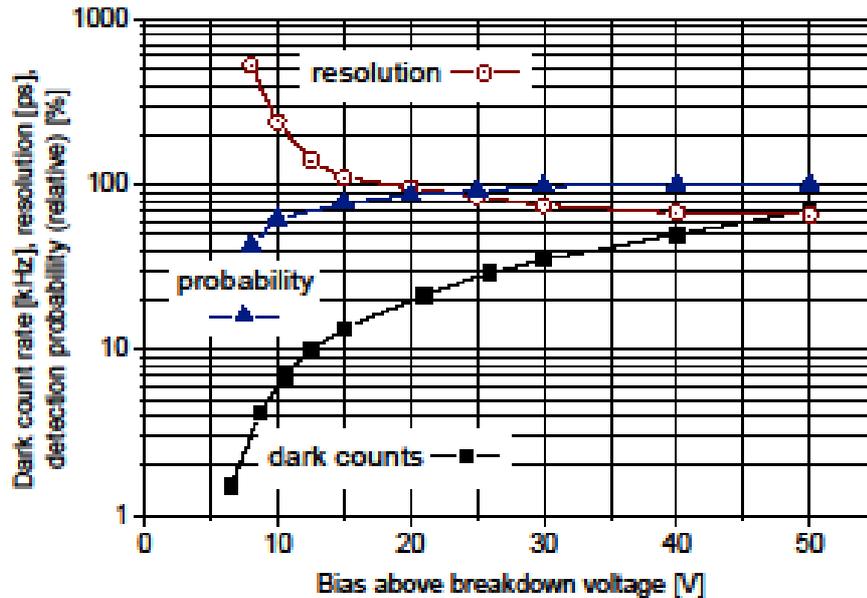


Figure 2 Basic photon counting parameters of a high photon detection probability photon counter based on silicon avalanche photodiode

The detection delay stability of an entire TCSPC chain in a form of time deviation TDEV is leveling at $TDEV < 800$ fs for averaging times of one hour. The temperature coefficient of 0.5 ± 0.1 ps/K was determined. The timing performance listed above enables to use this detector package also in Lunar laser ranging.

The detector package has been installed in the satellite laser ranging station in Graz Lustbühel, Austria (Kirchner et al., 2012). The laser system receiver optics has been aligned accordingly. The detector lower dark count rate and higher photon detection efficiency in comparison to the detectors used for routine satellite laser ranging has been noticed (Kirchner et al., 1997). The non-cooperative target distance ranged from 890 up to 2560 km. The targets having a cross section as low as 0.3 m^2 have been tracked. The echo rate in space debris laser ranging was in a range of 0.3 % to 26 % depending on target cross section and range. The ranging precision was limited by the target size and structure to 0.3 to 4 meters.

Photon counting detectors on InGaAs

Application of a near infrared wavelength of 1064 nm /fundamental wavelength of NdYAG laser/ seems to be an attractive option for space debris laser tracking. In comparison to the application of the second harmonic wavelength of the same laser the experiment energy budget is 4 to 6 times in favor of the fundamental wavelength; (photon energy 2x, SHG conversion efficiency $\sim 2x$, atmospheric two way attenuation up to $\sim 1.5x$). Thus once the photon counting detector can provide the detection efficiency $> 15\%$ @ 1064 nm the overall energy budget is better for the fundamental wavelength. The InGaAs based solid state photon counters have been developed for various applications since last two decades (Prochazka 2001). The photon detection efficiency exceeding 20% and sub-ns timing are achievable now. However, the detector active area is usually limited to a diameter of 30 μm . This represents a challenge for laser ranging applications. Several SLR sites have tested InGaAs based detectors use for space debris tracking. Up to now the overall system performance was not convincing in comparison to a standard setup operating on a second harmonic wavelength. The development of InGaAs solid state photon counters is still in progress, larger apertures (60 μm) and higher timing resolutions are expected to be available soon.

Photon counting detectors on Ge

Solid state photon counter based on germanium structure have been used for cm precision SLR at the wavelength of 1540 nm since nineties (Prochazka I. et al, 1996; Kunimori H.,et al, 2000). The very first space debris laser tracking at the wavelength of 1540 has been carried out using this type of detector (B.Greene, private communication). The detector active area is acceptable - typically 100 μm in diameter, the detector needs cryogenic cooling down to 77 K, liquid nitrogen cryostat is used. Unfortunately the photon detection efficiency is not exceeding 10% at 1540 nm wavelength.



Figure 3 Germanium semiconductor based photon counting detector in liquid nitrogen cooled cryostat. The height of the cryostat is 250 mm.

Superconducting solid state photon counters

The superconducting nanowire single photon detectors seem to be an attractive option for echo signal detectors for space debris laser ranging system operating at the 1540 nm wavelength in a near future. The promising new technology enables to create picosecond timing resolution and highly sensitive photon counters. The photon detection efficiency exceeding 70% @ 1540 nm has been reached (Bulgarini G., 2015).

There are two “bottlenecks” for applications of these detectors for SLR and similar applications:

1. The structure has to be cooled down to a liquid helium temperature of 4 K or even lower. Several laboratories are constructing closed cycle compact cryostats including the space qualified version.



Figure 4. Example of a closed cycle compact cryostats developed by a Single Quantum BV, Delft, Netherlands, (Bulgarini G., 2015).

2. The active area of existing detectors is really small, typically a square having (sub)micron edges. Numerous techniques are implemented in an attempt to create larger active area detectors: meanders, spirals and many others. The authors (Bulgarini G., 2015) are quite optimistic they are promising detectors having an active area of $50 \mu\text{m}$ in diameter in a near future. This number seems to be a realistic minimum for foreseen applications.

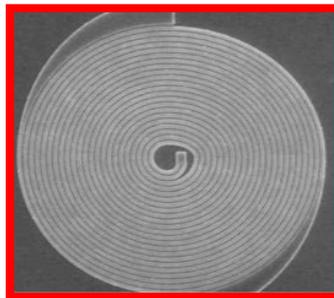


Figure 5. Topology of a “large area” superconducting nanowire single photon detectors, structure diameter of $10 \mu\text{m}$.

First attempts have been reported to use superconducting nanowire single photon detectors for laser ranging (Zhang Z., 2015). The optical coupling of receiving telescope output to the detector input aperture was the most limiting factor, as expected.

Conclusion

We are reporting design, construction and performance of various solid state photon counting detector packages suitable for laser tracking of orbiting space debris. A new version of SPAD detector optimized for high photon detection probability is described. It provides photon detection probability exceeding 70% at 532 nm wavelength. The foreseen new systems for orbiting space debris laser tracking are expected to operate on near infrared wavelengths 1064nm or 1540 nm. For 1064 nm wavelength region the InGaAs based semiconducting photon counters are promising candidates. The advantage of their use is an expected gain in overall energy budget 4 to 6 times using existing laser transmitters and SLR systems in comparison to a use of silicon based semiconducting photon counters on a second harmonic wavelength. The advantage of a wavelength of 1540 nm is availability of high power lasers and higher tolerance of human eyes to exposures by

this wavelength. The superconducting nanowire single photon detectors are an option for high photon detection efficiency exceeding 70% at this wavelength. The critical limitation in application of this type of detectors is their active area size, which is limited to several microns recently.

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